



# FROM RE FORECASTS TO GRID OPERATIONS - STRENGTHENING SCHEDULING, BALANCING AND GRID STABILITY

**24<sup>th</sup> September 2026**

**SUGATA BHATTACHARYA, MANAGER (SO)  
NRLDC, GRID CONTROLLER OF INDIA LTD.**



Source: GO15

- 1 National Synchronous Grid
- Electricity Generation
- 3 Electricity Consumption
- Installed Generation Capacity
- Transmission System
- 4 Solar Generation
- Wind Generation
- 6 Hydro Generation
- 10 Pumped Storage Installed Capacity

Source: IEA World Energy Outlook 2025

# DIMENSIONS OF THE INDIAN POWER SYSTEMS

**~554 GW**

generation capacity

**> 6 TWh**

daily energy met

**270 GW+**

peak demand

**4,99,451 ckm+**

EHV transmission

**~257 GW**

renewables

(incl. ~50 GW large Hydro)

**~ 120 GW**

inter-regional capacity

**14**

HVDCs

**3.2 million km<sup>2</sup>**

area footprint

**3**

power exchanges

**162,000+**

market transactions

**1.4 Billion+**

people served

**4.5 GW+**

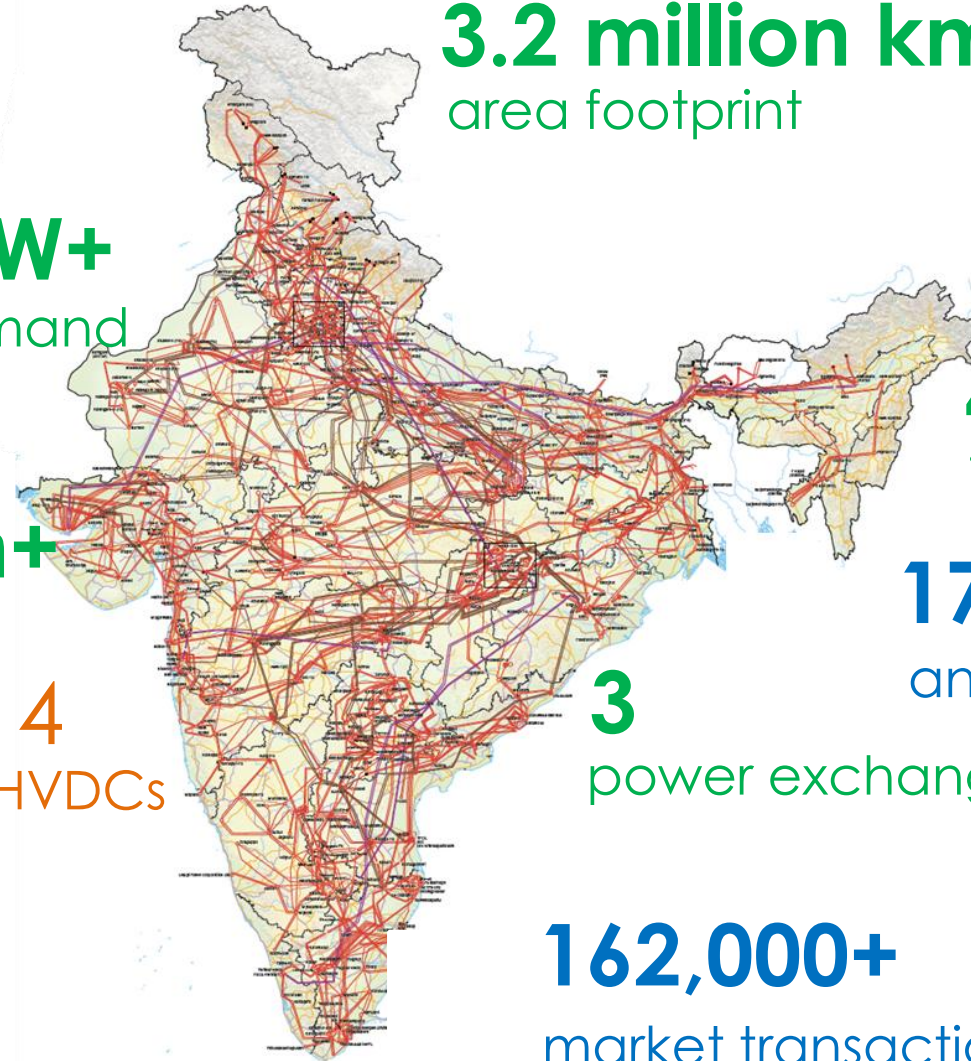
international exchanges

**171 TWh+**

annual market trades

**6000+**

market participants



# EVOLUTION OF GRID & SYSTEM OPERATION

**1947-1964**

- State Grids
- Isolated Nature

Monolithic (SEBs)

SEB – State Electricity Board

**1964-2003**

- Regional Grids
- Inter-state connections

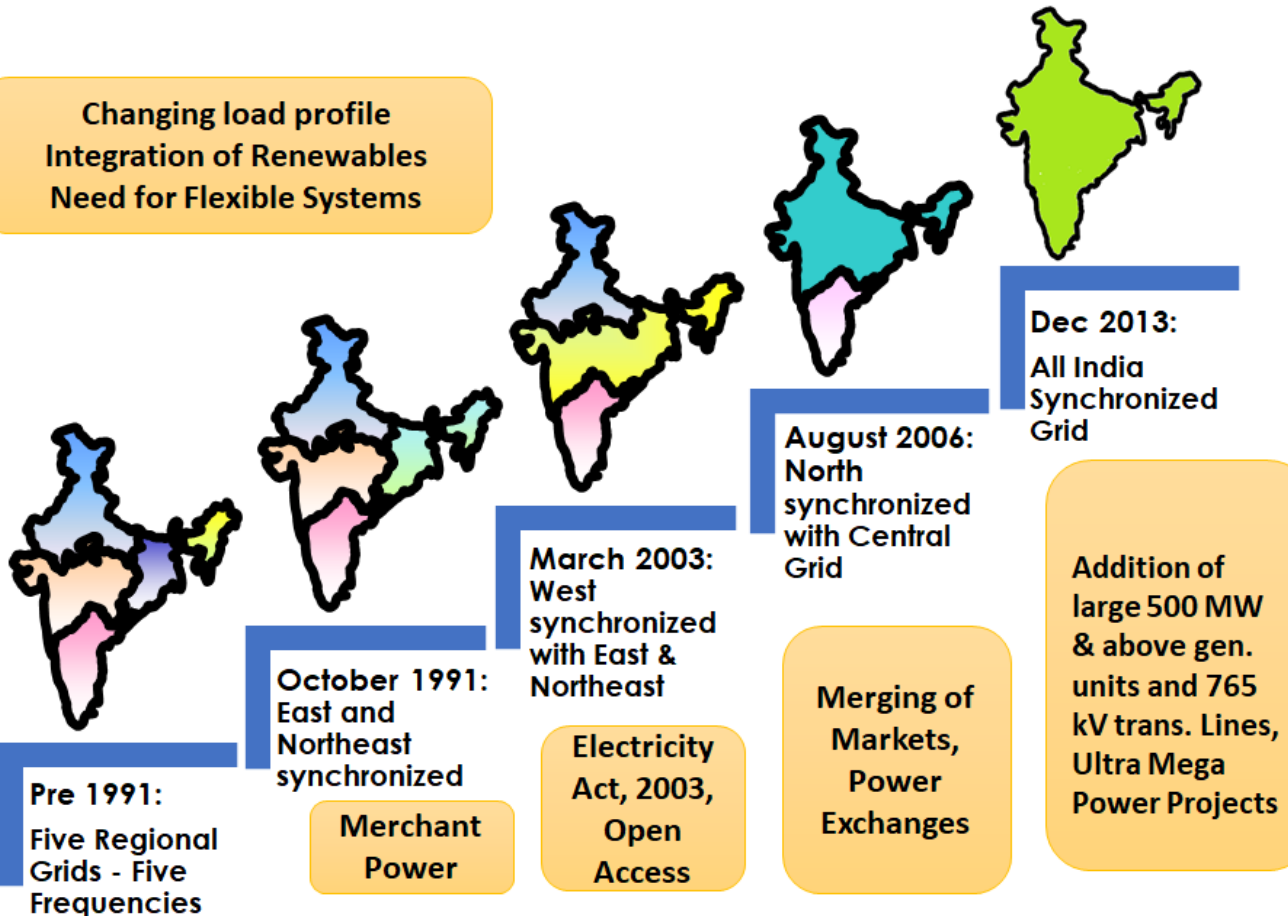
Competition (PSUs & Private)

PSU – Public Sector Undertaking

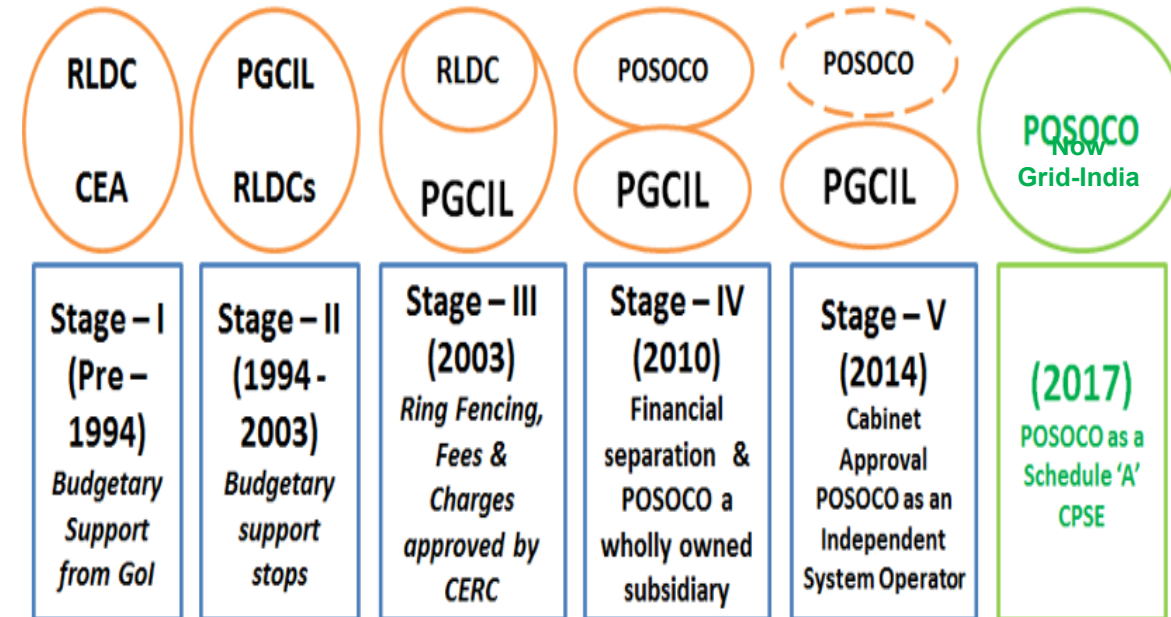
**2003 – Present**

- National Grid
- International connections

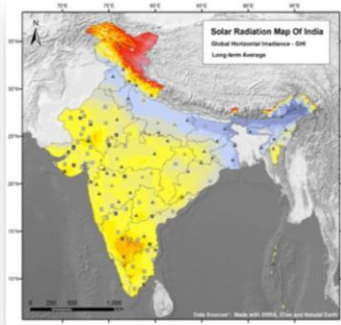
Changing load profile  
Integration of Renewables  
Need for Flexible Systems



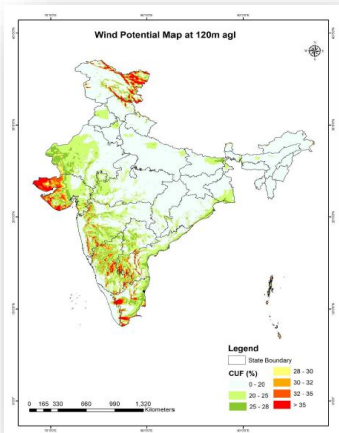
## Transition from Transmission System Operator (TSO) to Independent System Operator (ISO) Model



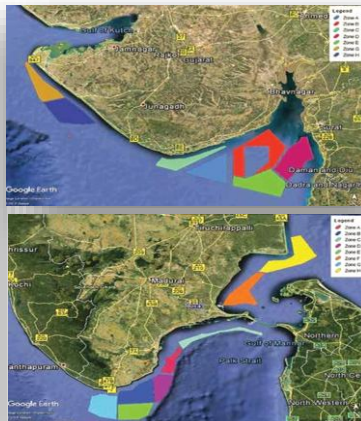
## Solar Radiation Atlas



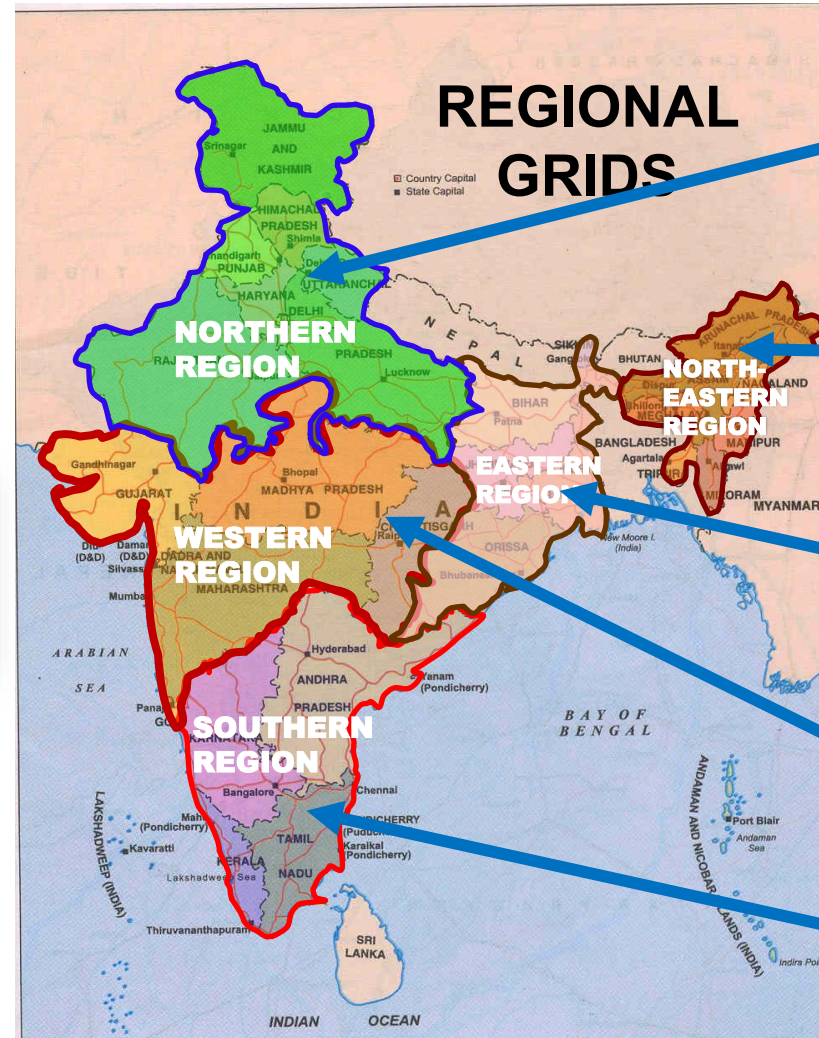
## Wind Atlas



## Offshore Wind



**High Wind and Solar potential in Northern, Western and Southern Regions**



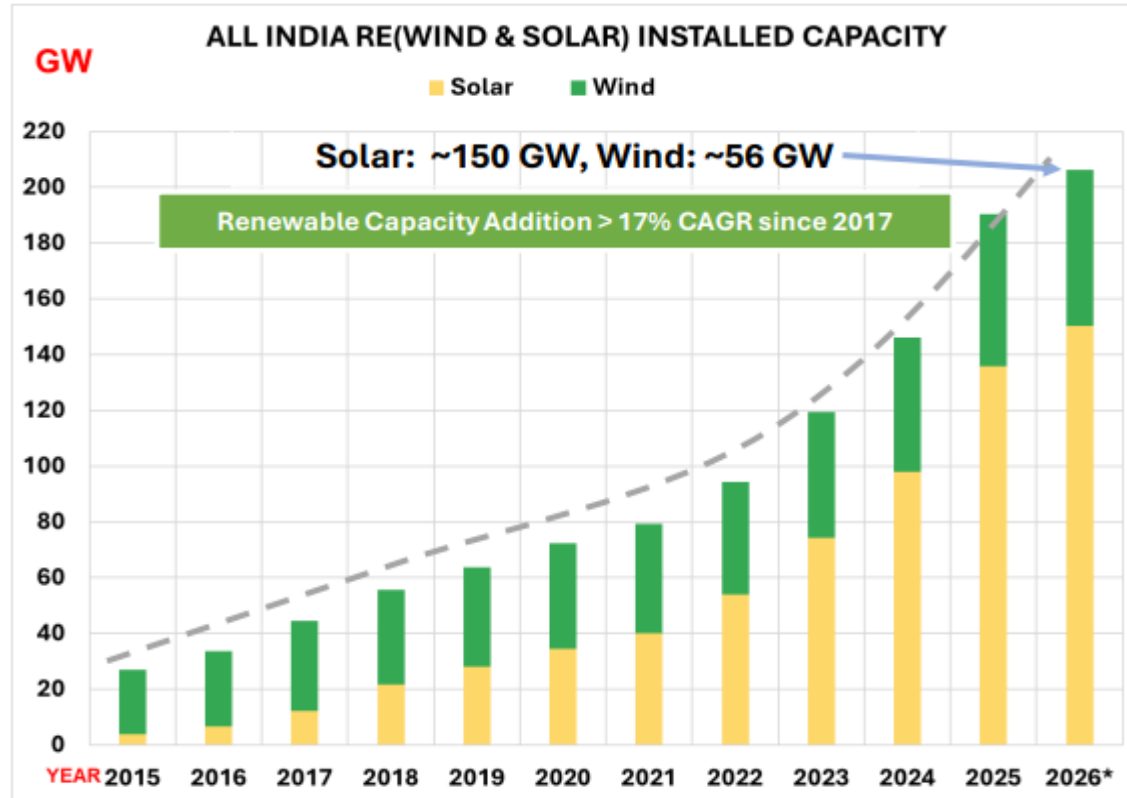
Snow fed - run-of-the-river hydro  
Highly weather sensitive load  
Adverse weather conditions: Floods, Fog & Thunderstorms  
Renewable Rich States - Wind/Solar

High hydro potential  
Mountainous Terrain  
Power evacuation challenge

High coal reserves  
Pit head base load plants

Industrial and Agricultural load  
Renewable Rich States - Wind/Solar  
Large thermal generation capacity

Industrial and Agricultural load  
Monsoon dependent hydro  
Renewable Rich States - Wind/Solar

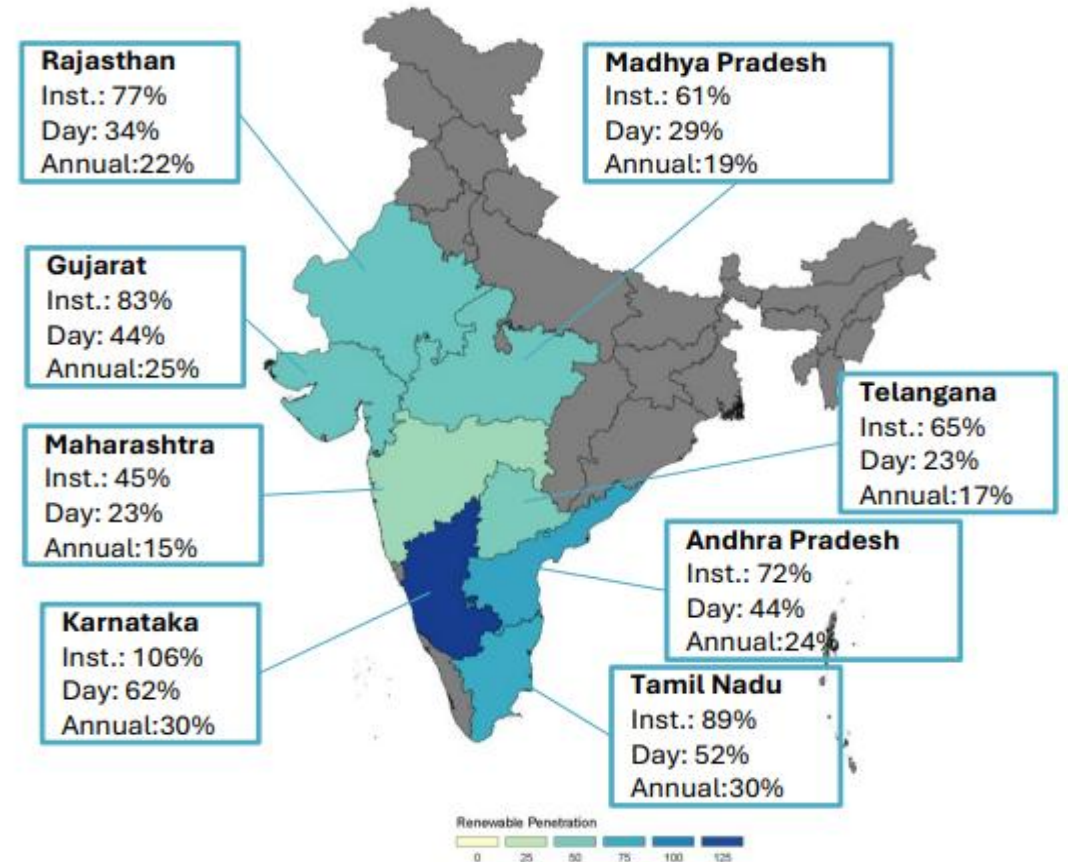


Source: CEA Installed Capacity Report (data as on Dec 2025)  
[Installed Capacity Report - Central Electricity Authority](#)

**Highest All India Instantaneous VRE (Solar + Wind) penetration of ~42.79% recorded - 13<sup>th</sup> July 2026**

**Highest All India Instantaneous RE (Solar + Wind + Hydro) penetration of ~52.25% recorded - 27<sup>th</sup> August 2026**

## Maximum Wind + Solar penetration in instantaneous MW and energy (day/year) terms – FY 2025-26



**500 GW non-fossil capacity by 2030**  
Including ~285 GW Solar & ~93 GW Wind

# INDIA'S ENERGY TRANSITION ROADMAP

till April 2026\* 2030

| Resource              | Mar-2026   | Mar-2030   | Mar-2036    |
|-----------------------|------------|------------|-------------|
| Hydro (including PSP) | 51         | 81         | 172         |
| Solar PV              | 150        | 285        | 509         |
| Wind                  | 56         | 93         | 155         |
| Other RES             | 17         | 18         | 22          |
| Nuclear               | 9          | 13         | 22          |
| Coal + Lignite        | 229        | 260        | 315         |
| Gas                   | 20         | 20         | 20          |
| <b>Total</b>          | <b>533</b> | <b>770</b> | <b>1215</b> |
| BESS                  | -          | 24         | 80          |

All capacities in GW

Source: CEA LONG-TERM NATIONAL RESOURCE ADEQUACY PLAN (2026-27 to 2035-36)

Rooftop Solar I/C (as on Mar 2026): 25.73 GW

|                                                                                       |                                                          |                    |                   |
|---------------------------------------------------------------------------------------|----------------------------------------------------------|--------------------|-------------------|
|    | Maximum Demand Met (GW)                                  | ~256 <sup>#</sup>  | 334 <sup>^</sup>  |
|    | Electricity Consumption for preceding FY (BU)            | ~1707 <sup>#</sup> | 1949 <sup>^</sup> |
|    | Total Generation Installed Capacity (GW)                 | 533 <sup>*</sup>   | 770               |
|    | Non-fossil Fuel Based Generation Installed Capacity (GW) | 283                | 500               |
|  | Wind & Solar Installed Capacity (GW)                     | 206                | 378               |

Source: <sup>#</sup> Operational Data of Grid-India

<sup>\*</sup> As on Mar 2026, CEA Installed Capacity Report

<sup>^</sup> 20<sup>th</sup> EPS Survey by CEA

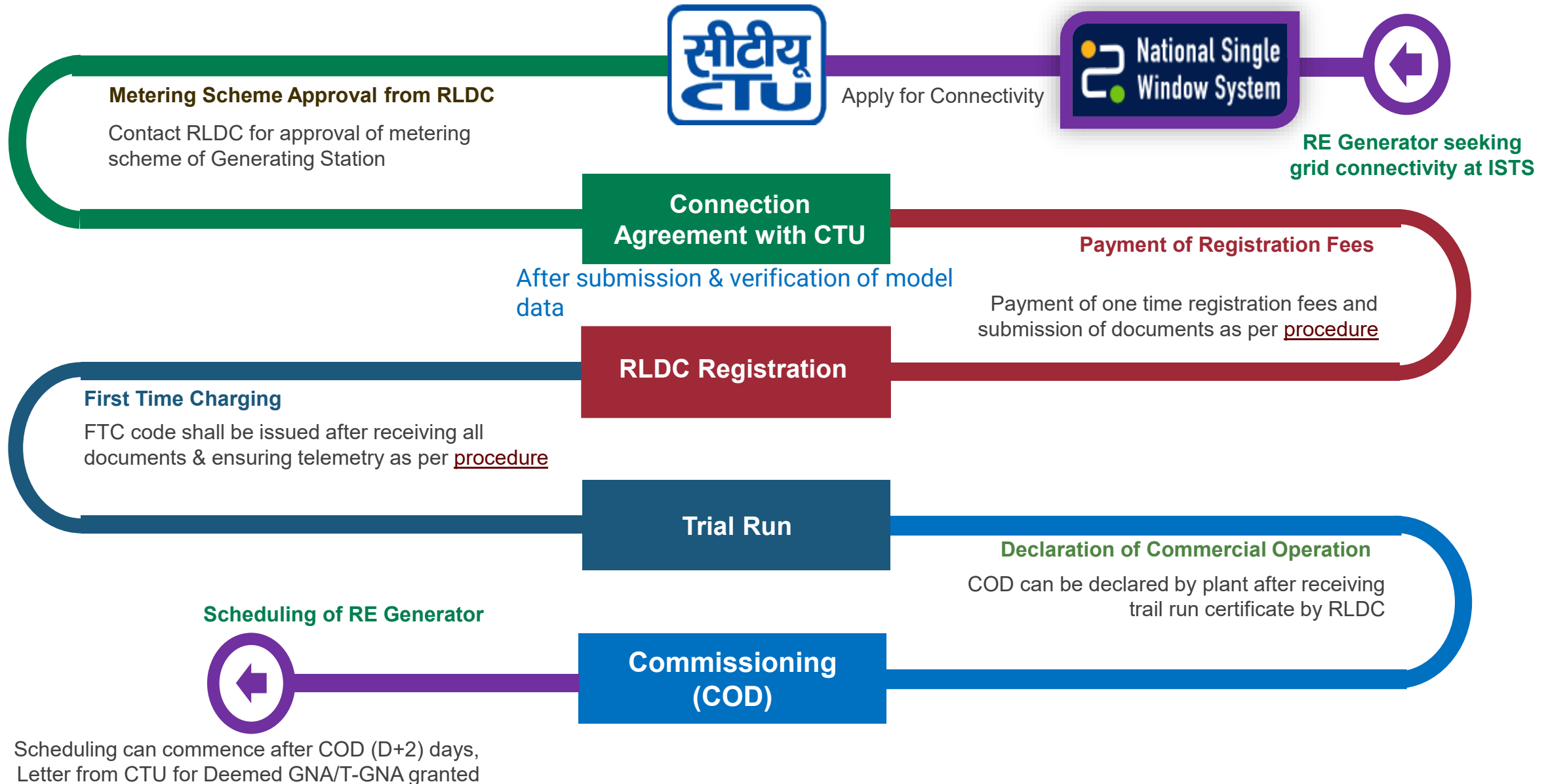
## CEA Connectivity Standards widely cover the technical requirements



**Standards and regulations to keep pace with the rapid technological advancements through regular updates:**

- ✓ New IBR interfacing loads - GH2 Loads, EV Charging Stations, flexibility from Data Centers etc.
- ✓ IBR Technology – Grid Forming, Hybrid HVDCs etc.

# RE GENERATOR- GRID INTEGRATION PROCESS



# GRID ACCESS & SCHEDULING ACTIVITY

Use it or lose it !

Access and PPA delinked

Flexibility

Optimization

Market Access

Freedom & Choice

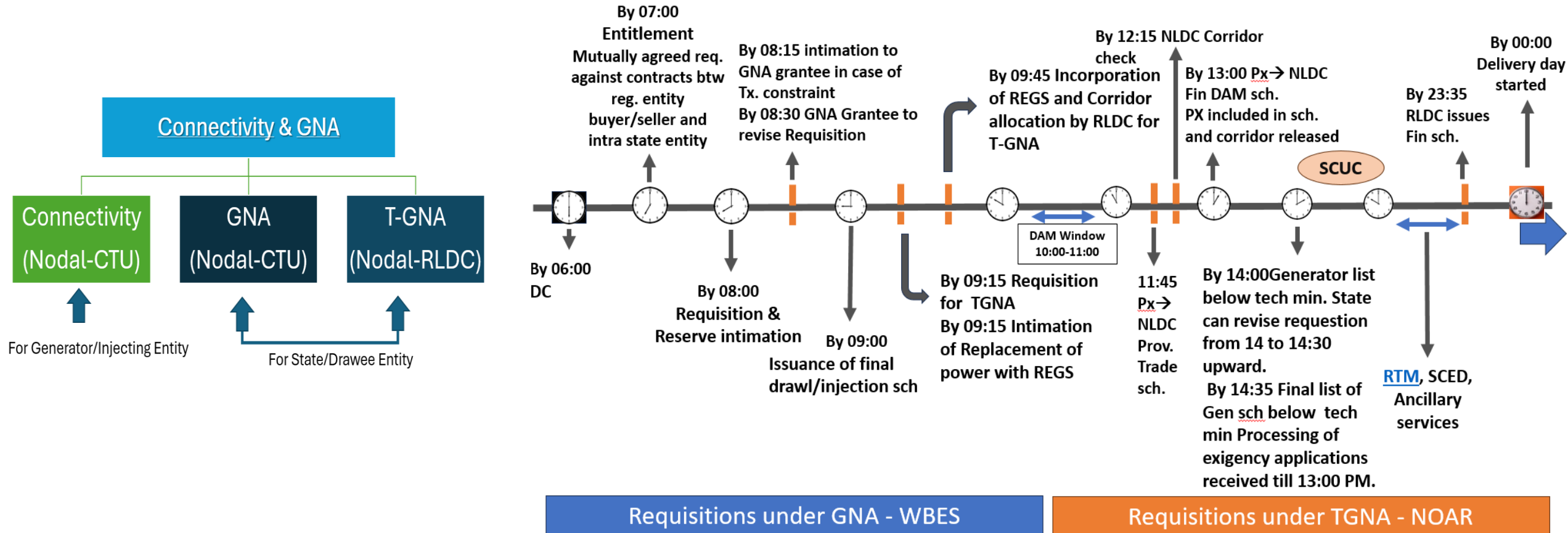
Balancing

Benefit Sharing

Payment Security – Financial Sustainability

Grid Access – Scheduling Pre-requisite

Scheduling Timeline



## 1. Resource Adequacy and Balancing Requirements

- **Resource crunch** during non-solar period
- **Solar:** Large cloud cover, seasonal variations, solar eclipse, capacity shortage in non-solar hours
- **Wind:** Wind speed fluctuations, weather patterns

## 2. Generation and Demand Side Flexibility

- Increasing generation flexibility requirement
- Increasing uncertainty on load side (Impact of behind the meter resources)

## 3. Impact on Grid Stability

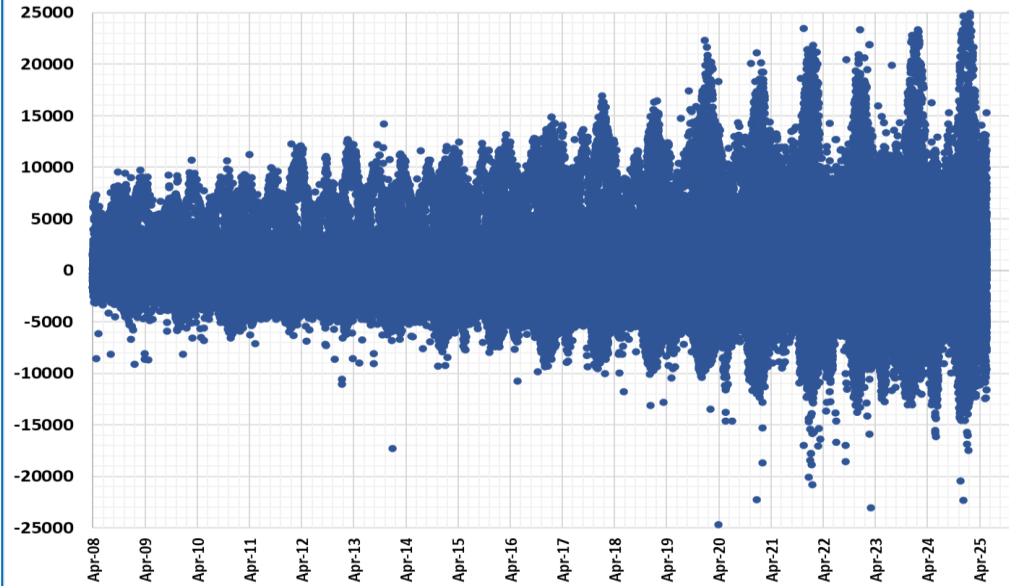
- Concentrated nature of RE capacity addition
- Voltage regulation challenges
- Non-compliance leading to grid disturbances
- Oscillations, Controller Interactions

## 4. Transmission Planning

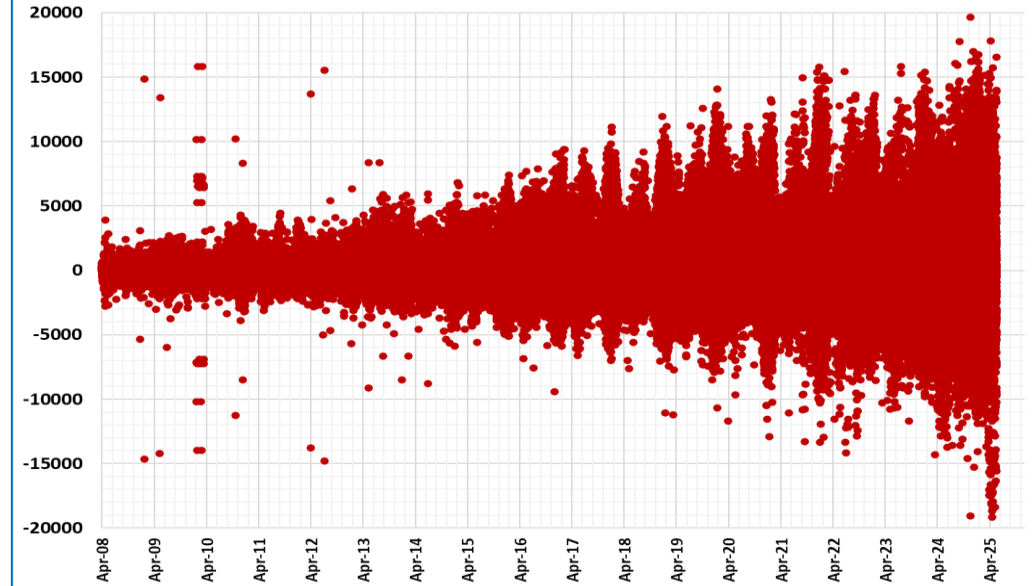
- Challenges in ensuring adequate system strength
- Behavioral change in corridor flow patterns

# OPERATIONAL AND PLANNING CHALLENGES : GENERATION AND DEMAND SIDE

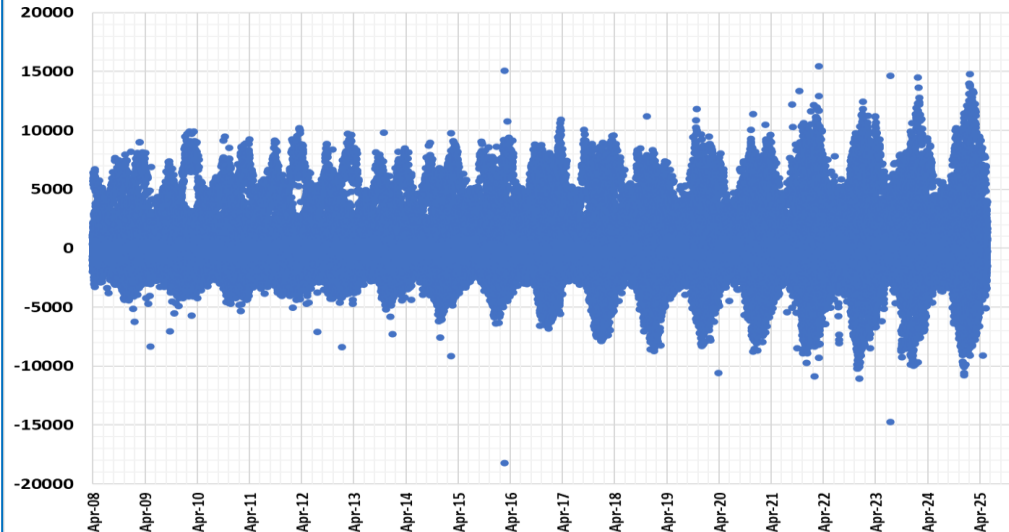
Hourly Ramp in All India Demand Met 2008-2025



Hourly Ramp in All India Thermal Generation 2008-2025

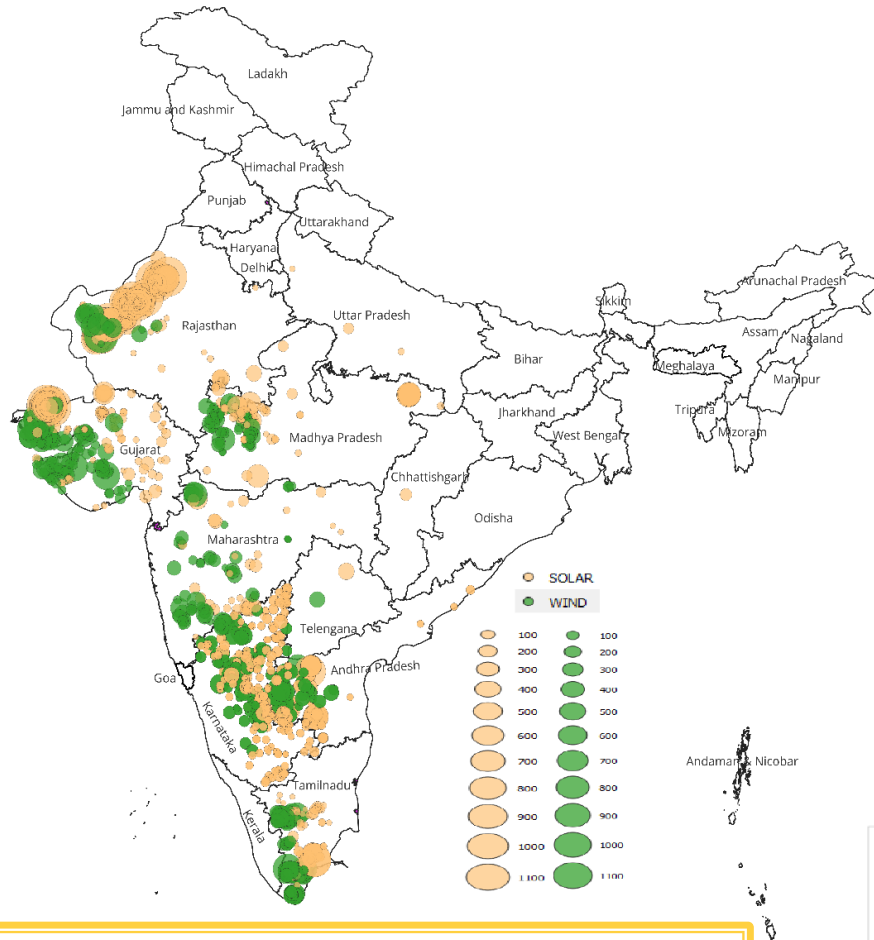


Hourly Ramp in All India Hydro Generation 2008-2025

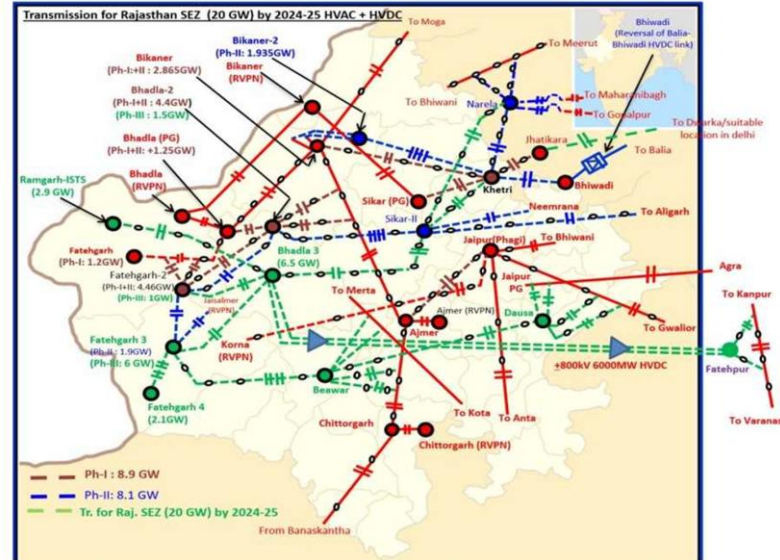


- Increase in morning peak, night lean load remaining same.
- Demand variability of  $\sim 25$  GW/hour
- $\sim 40$ -50 GW daily flexibility requirement
- Variability in Generation:
  - Thermal: Increased in both directions
  - Hydro: Positive side is almost constant
- Rising uncertainty on load side (Impact of behind the meter resources) : Rooftop Solar

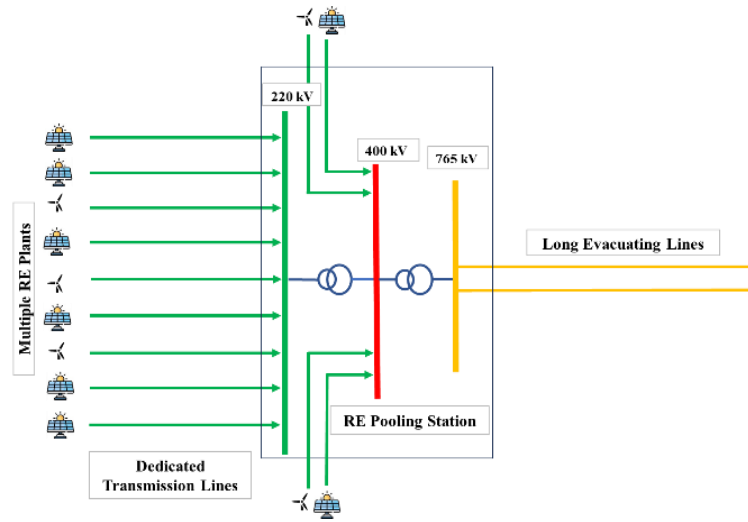
# OPERATIONAL AND PLANNING CHALLENGES : TRANSMISSION SIDE



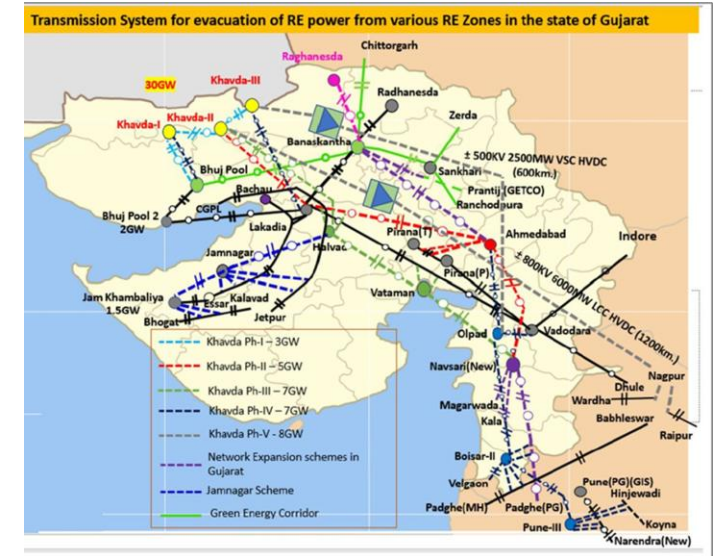
- ~115 GW solar generation capacity in close vicinity in Rajasthan by 2030
- ~50 GW generation capacity within 140-150 km radius in Gujarat (Khavda, Bhuj area) by 2030
- ~42 GW RE generation capacity within 30-40 km radius coming up in Khavda region (Gujarat) by 2030



Map of NR (Rajasthan) ISTS RE Complex



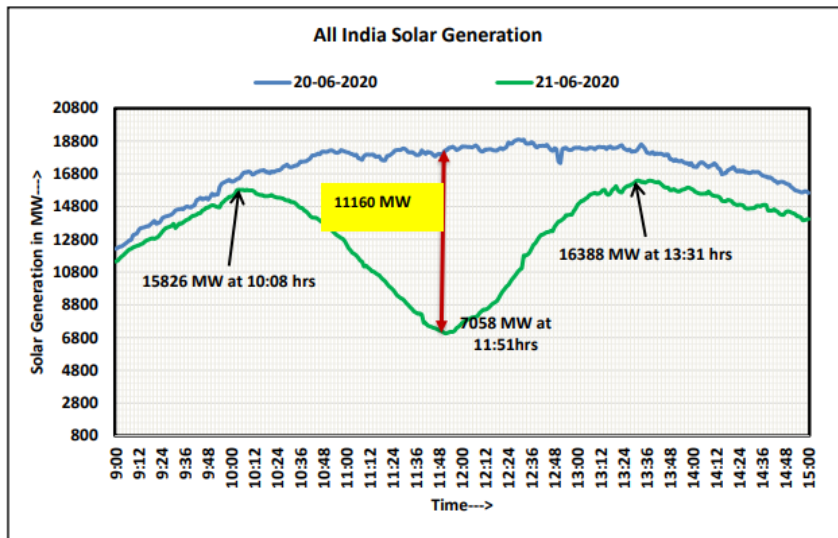
**Periodic Revisions in T-GNA Margins and Evacuation Limits from ISTS RE Complex**



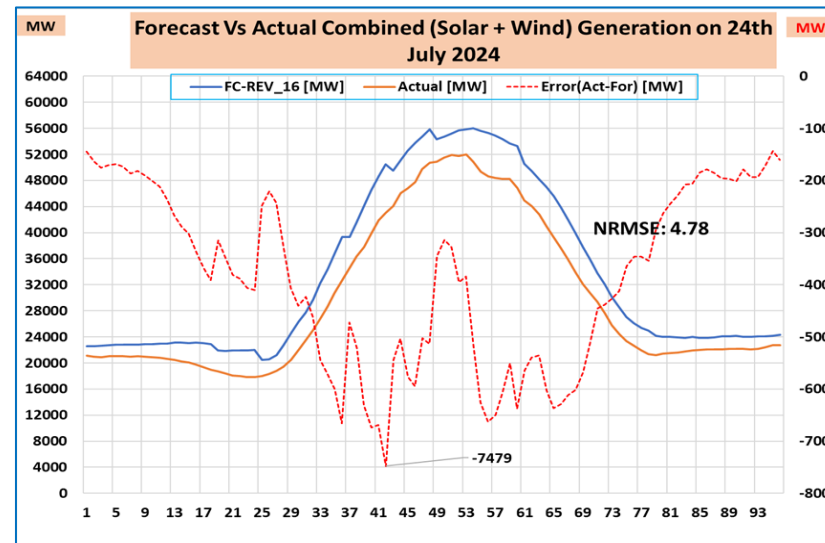
Map of WR (Khavda, Gujarat) ISTS RE Complex

**Unique VRE capacity addition in India in terms of:**

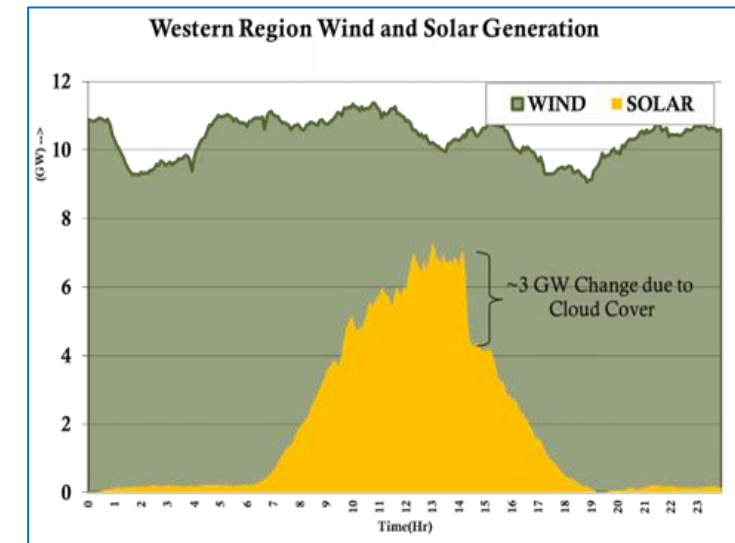
- ✓ Concentrated RE zones
- ✓ Large RE pooling stations at the EHV level (4000 – 8000 MW)
- ✓ Substations aggregating power from multiple pooling stations
- ✓ Remotely located VRE plants, far from load centres
- ✓ Long UHV/EHV lines to evacuate intermittent/variable RE power



All India Solar generation on 20.06.20 vs. 21.06.20 (Solar Eclipse Day)



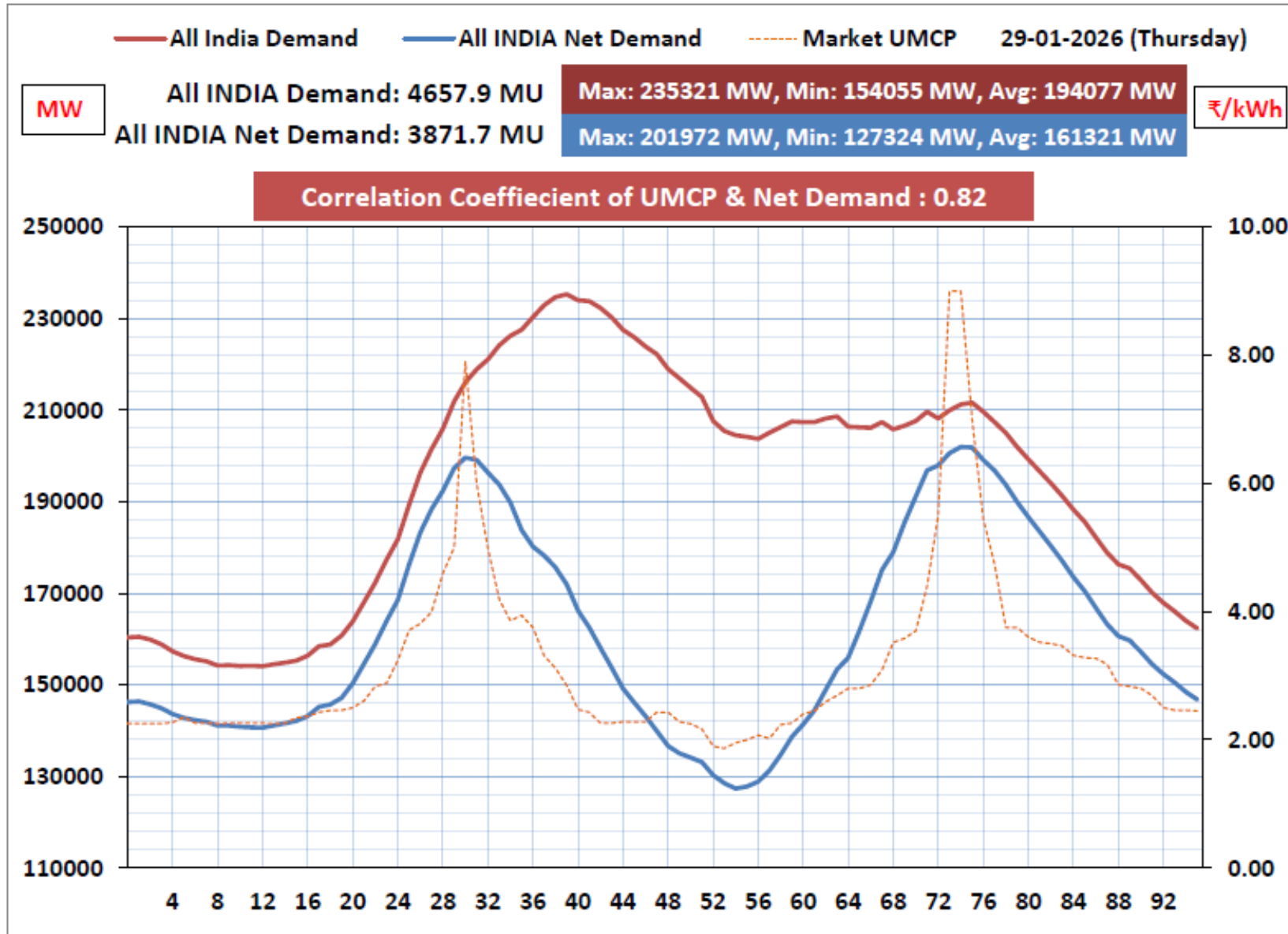
Predictability: Need for precise predictions of how much power will be fed into the grid at any given moment is important



Intermittency: Vulnerable to weather conditions  
Solar power is susceptible to cloudy days & Wind power to calm days

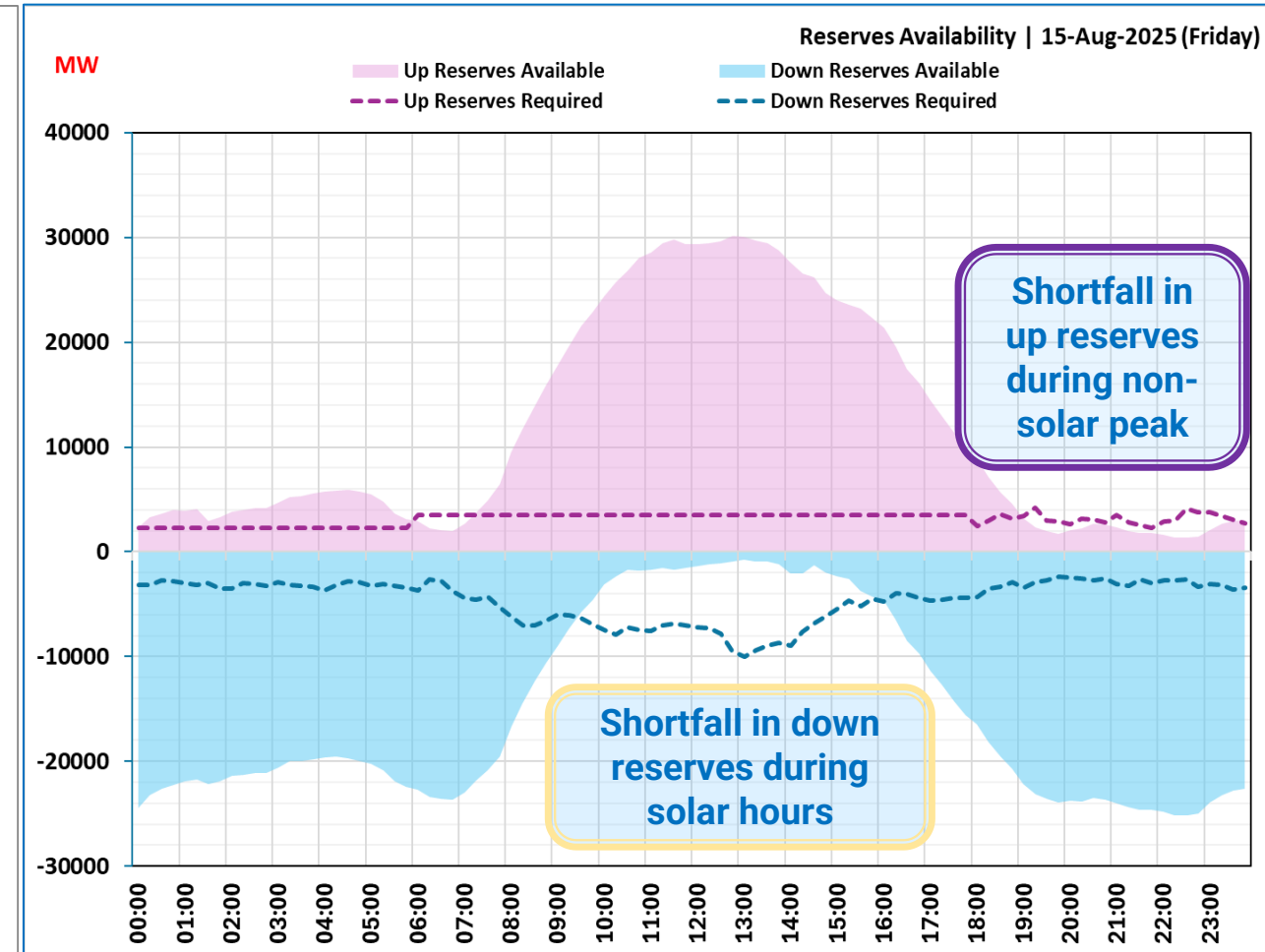
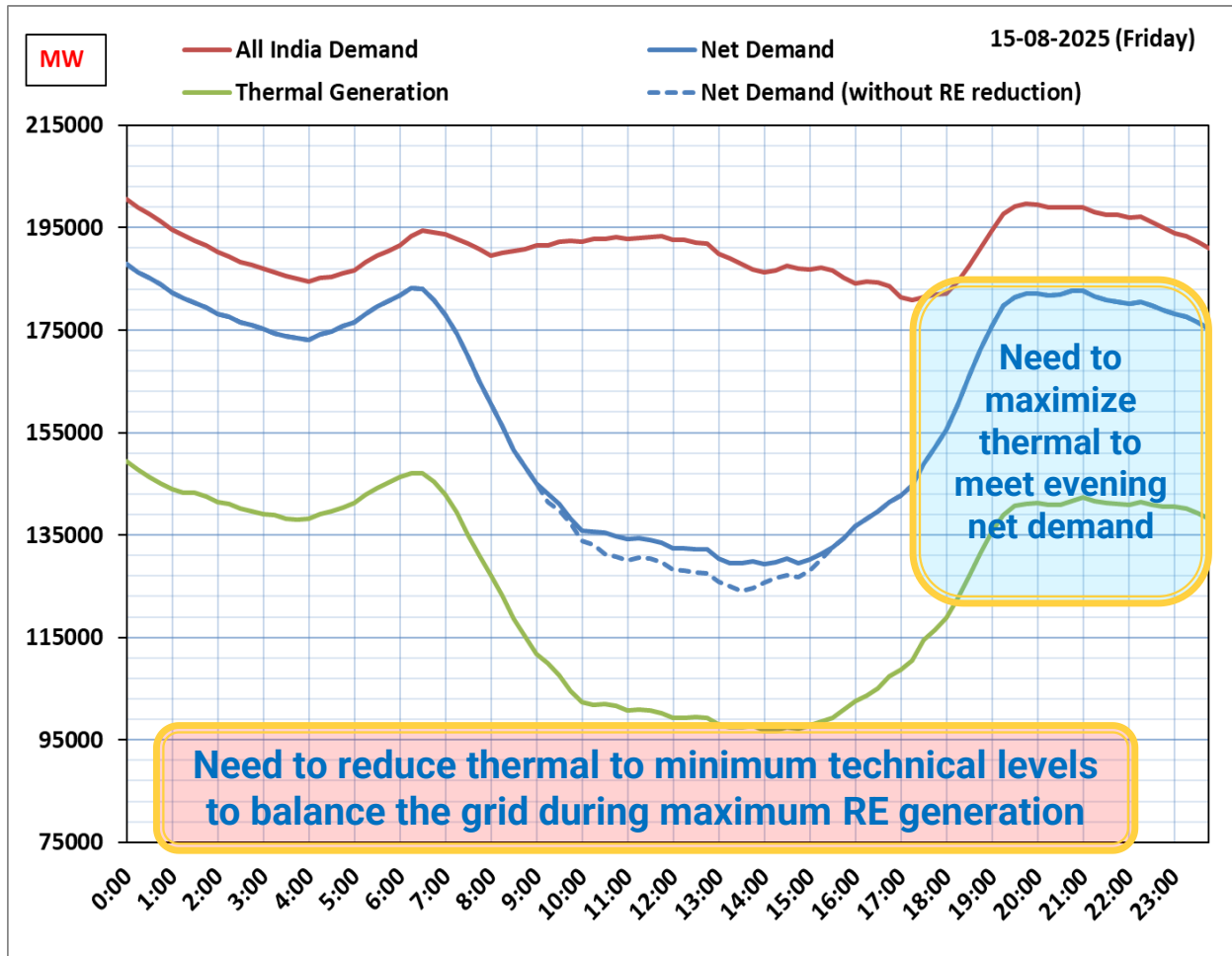
- ✓ With 1200+ GW solar & 450+ GW wind capacity addition by 2047, improvement in forecasts – both inter / intra-day forecasts as well as medium / long term weather year forecasts – is must for reliable system operation
- ✓ Multi-disciplinary collaboration among agencies like NCMRWF, ISRO, IMD, academic institutions, climate sciences etc. is critical for improving VRE forecast accuracy !!

# NET LOAD CURVE - EVOLUTION FROM “DUCK” TO “GIRAFFE”

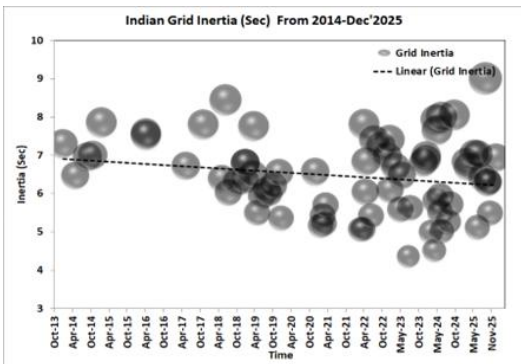
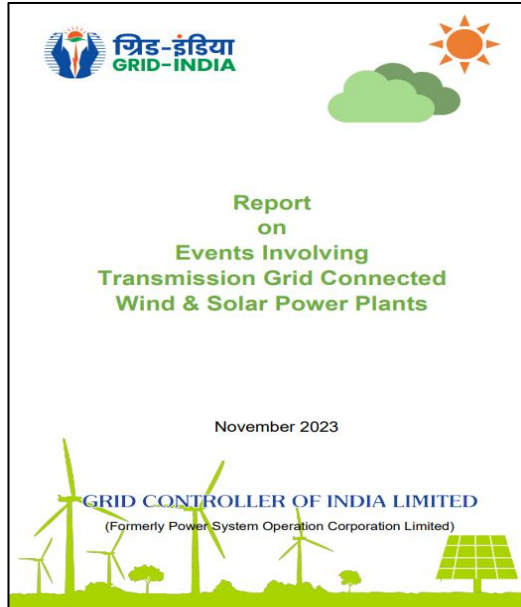


- Increasing “Duck Curve” Belly
- Issues in absorbing additional RE (solar) beyond a certain quantum
- Increasing difference b/w Max. and Min Demand
- In Solar Hours, no down margin available in Thermal stations

## Divergent challenges - Flexibility in solar hours and adequacy in non-solar hours !!

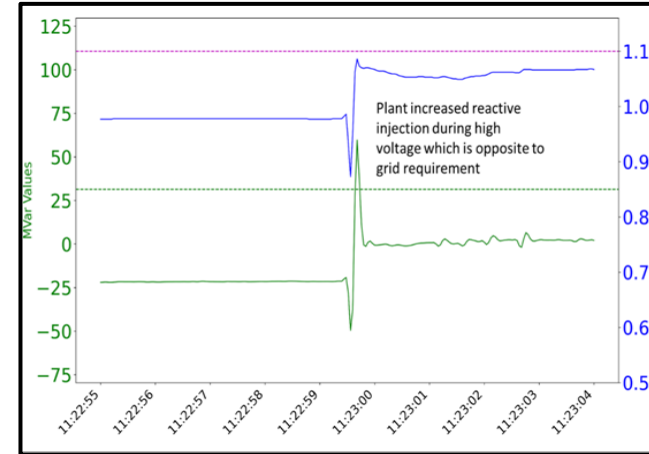
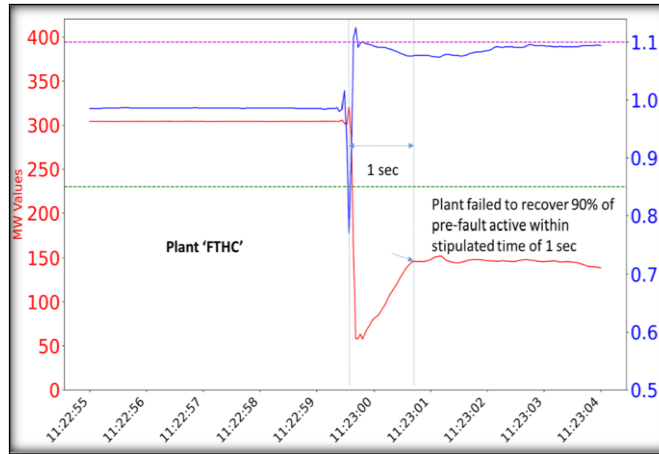


**Availability of reserves is critical for secure grid operation !!**



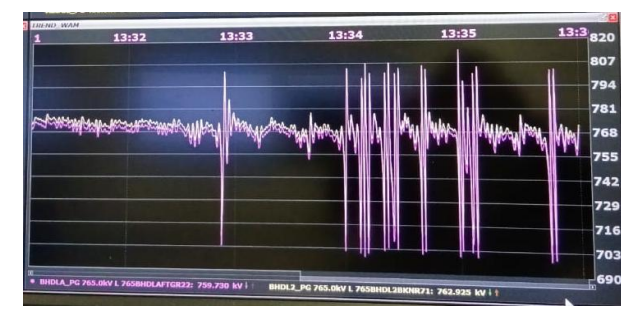
**Inertia in declining trend;**  
**~69 events** involving RE  
**generation** loss of above  
**1000 MW** between Jan'22  
 to Oct'25

## Fault-ride through failure of the RE plants, non-compliance to specified CEA Standards



- Inadequate and delayed reactive power support during ride through conditions
- Delayed active power recovery post-fault-clearance
- High voltage post-fault clearance leading to tripping of inverters on HVRT and transmission lines on over-voltage

## Forced voltage oscillations & voltage spikes in large RE complexes



## Protection coordination challenges in RE complexes

6000 MW Generation Loss in Rajasthan RE Complex on 11th Aug 2022:

- ❖ Most inverters failed to recover MW output within 1s after fault clearance (phase to phase fault in RE evacuating line)
- ❖ Due to a reduction in generation, the EHV network got offloaded, causing a further rise in voltage
- ❖ Sustained overvoltage led to significant generation loss (HVRT) and tripping of multiple EHV lines due to overvoltage
- ❖ Triggering of under-frequency load shedding (~750 MW)

# INDIA – SUSCEPTIBLE TO NATURAL DISASTERS

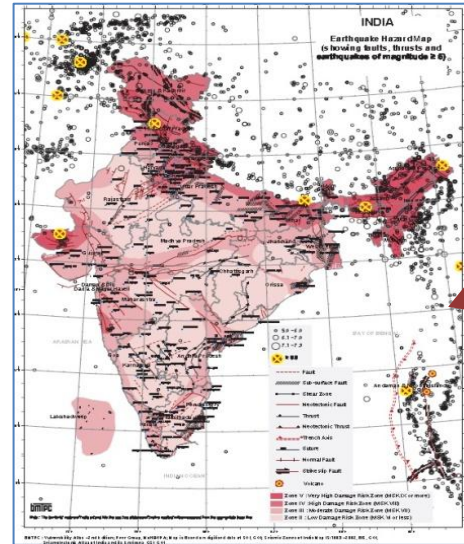
## Unique Climatic Regime

Two monsoon seasons  
(southwest & northeast monsoons)

Two cyclone seasons  
(pre & post monsoon cyclone seasons)

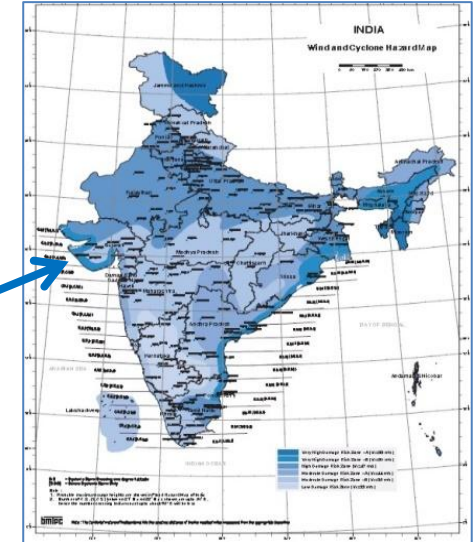
Hot weather season  
characterised by  
violent convective  
precipitation

Cold weather season  
characterised by  
violent snow storms in  
the mountains



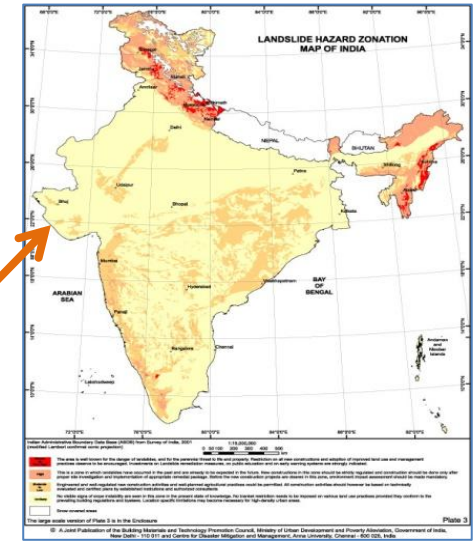
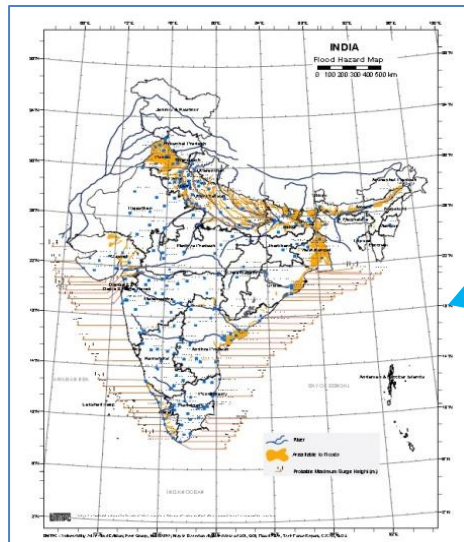
58 % of landmass prone  
to earthquake of  
moderate to very high  
intensity

8 % of landmass  
prone to cyclone  
and tsunami



12 % of landmass  
prone to flood and  
river erosion.

15 % of land mass is  
prone to land-slides and  
avalanches





**Potential economic impact of a large-scale generation loss event leading to black-out is immense and inherently non-quantifiable**

## Cyclones

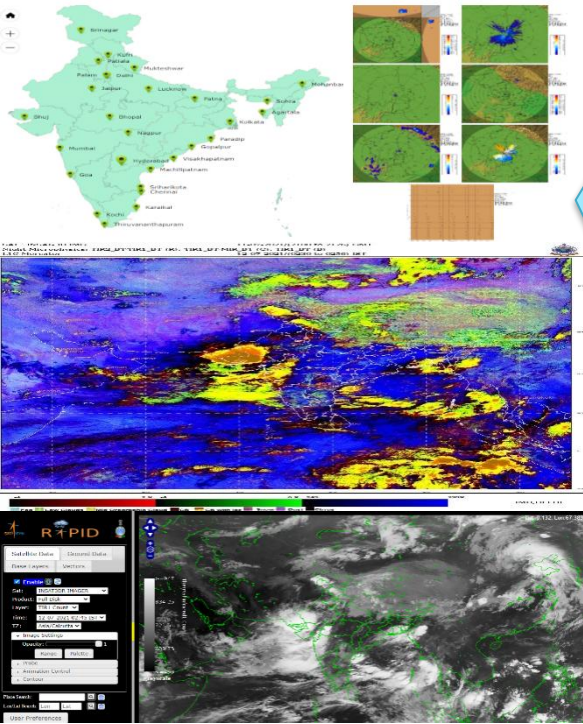
- **2025:** Fenal, Montha, Ditwah
- **2024:** Remal, Dana
- **2023:** Biparjoy, Michaung
- **2022:** Asani , Mandous
- **2021:** Tauktae , Yass
- **2020:** Amphan, Nivar
- **2019:** Fani, Bulbul
- **2018:** Titli, Gaja
- **2016:** Vardah
- **2014:** Hud-Hud
- **2013:** Phailin

## Floods

- **2025:** West Bengal, Himachal, Assam, Bihar
- **2023:** Chennai
- **2022:** Assam
- **2021:** Uttarakhand, Maharashtra
- **2020:** Assam, Telangana
- **2019:** Karnataka, Kerala
- **2018:** Kerala
- **2017:** Tamil Nadu
- **2016:** Assam
- **2015:** Tamil Nadu
- **2013:** Uttarakhand

## Earthquakes

| Date          | Affected Area                | Intensity |
|---------------|------------------------------|-----------|
| 03 Nov 2023   | India, Nepal                 | 5.7       |
| 28 April 2021 | India                        | 6.0       |
| 10 April 2018 | India                        | 4.6       |
| 03 Jan 2017   | India, Bangladesh            | 5.7       |
| 04 Jan 2016   | India, Myanmar, Bangladesh   | 6.7       |
| 26 Oct 2015   | India, Afghanistan, Pakistan | 7.7       |
| 12 May 2015   | India, Nepal                 | 7.3       |
| 01 May 2013   | India                        | 5.7       |



## Weather and Fog Challenges

The relationship between weather and energy usage is a never-ending cycle, Due to Heavy rain fall/ Thunder storm, sudden fall in Demand/Load crash occurs which creates problem of Over Voltage and Over frequency in grid.

When a fog occurs, the air humidity approaches to 100% and condensation tend to occur on surfaces exposed to the fog. The condensation also occur on the insulators which are supporting the transmission lines, leading in some cases to voltage breakdown and tripping of circuit breakers.

Apart from that some time due to Cyclone/Thunderstorm/High speed wind there is likely chances of tripping of multiple lines/bending or collapsing of tower, This type of climate condition put the system in High alert



Weather & Fog forecast and forecasting of likely climate conditions by IMD and ISRO

NRLDC

With the help of weather forecasting results NRLDC assesses its impacts on NR grid and take action accordingly, control room personnel as well as SLDCs got sensitized and alerted prior to any change in climate, This ensures the secure and reliable operation of Grid.





## NR RE Integration Challenges

### Variability

Power plants that run on fuel (along with some hydro and geothermal plants) can be ramped up and down on command. They are, in the "dispatchable." But RE plants produce power only when the wind is blowing or the sun is shining. Grid operators don't control VRE, they accommodate it, which requires some agility.

### Uncertainty

The output of RE plants cannot be predicted with perfect accuracy in day-ahead and day-of forecasts, so grid operators have to keep excess reserve running just in case.

### Location-specificity

Sun and wind are stronger (and thus more economical) in some places than in others — and not always in places that have the necessary transmission infrastructure to get the power to where it's needed.

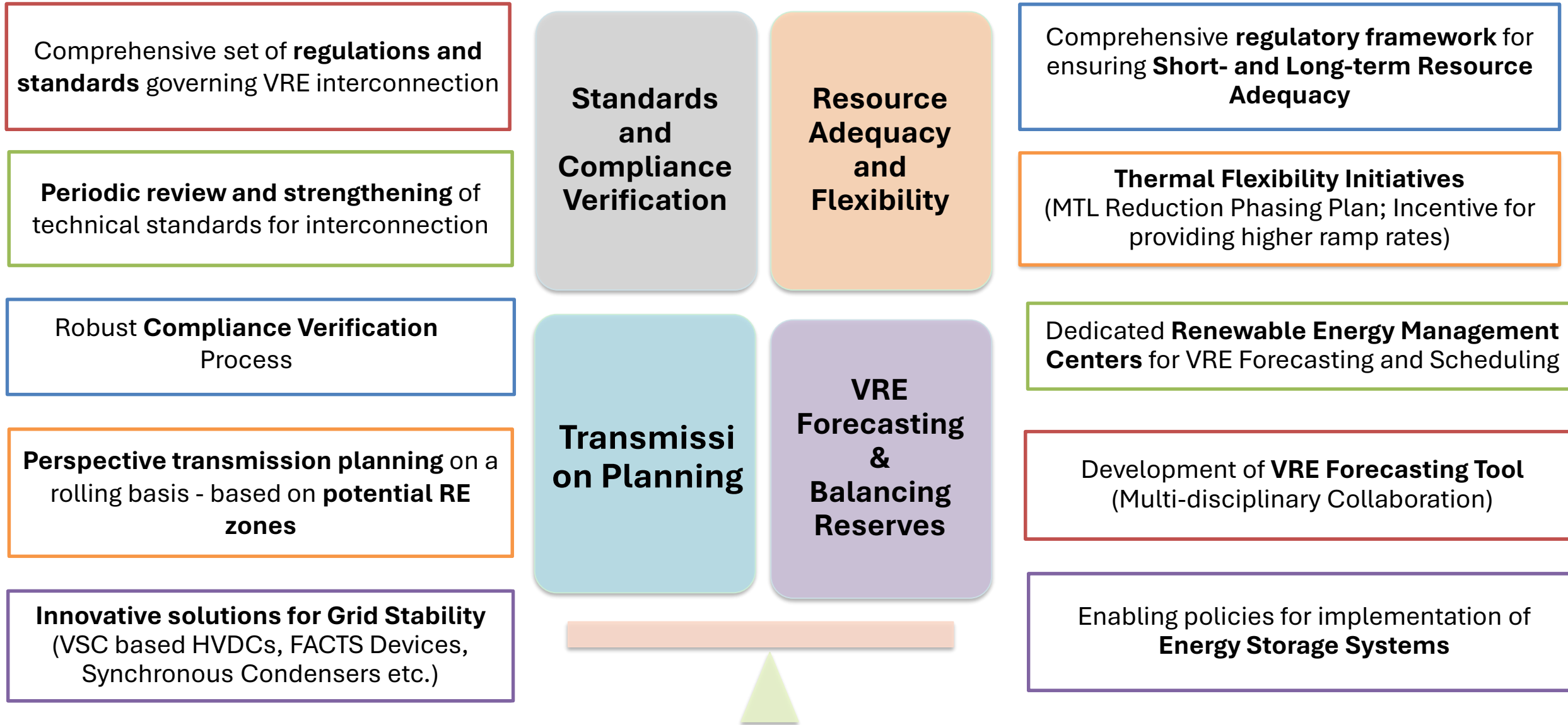
### Nonsynchronous generation

Conventional generators provide voltage support and frequency control to the grid. RE generators can too, potentially, but it's an additional capital investment.

### Low capacity factor

RE plants only run when sun or wind cooperates  
Because of the low capacity factor of RE, conventional plants are needed to take up the slack, but because of the high output of RE in peak hours, conventional plants sometimes don't get to run as often as needed to recover costs.

# KEY INITIATIVES TO FACILITATE SMOOTH RE INTEGRATION



## Grid Stability and Reliability:

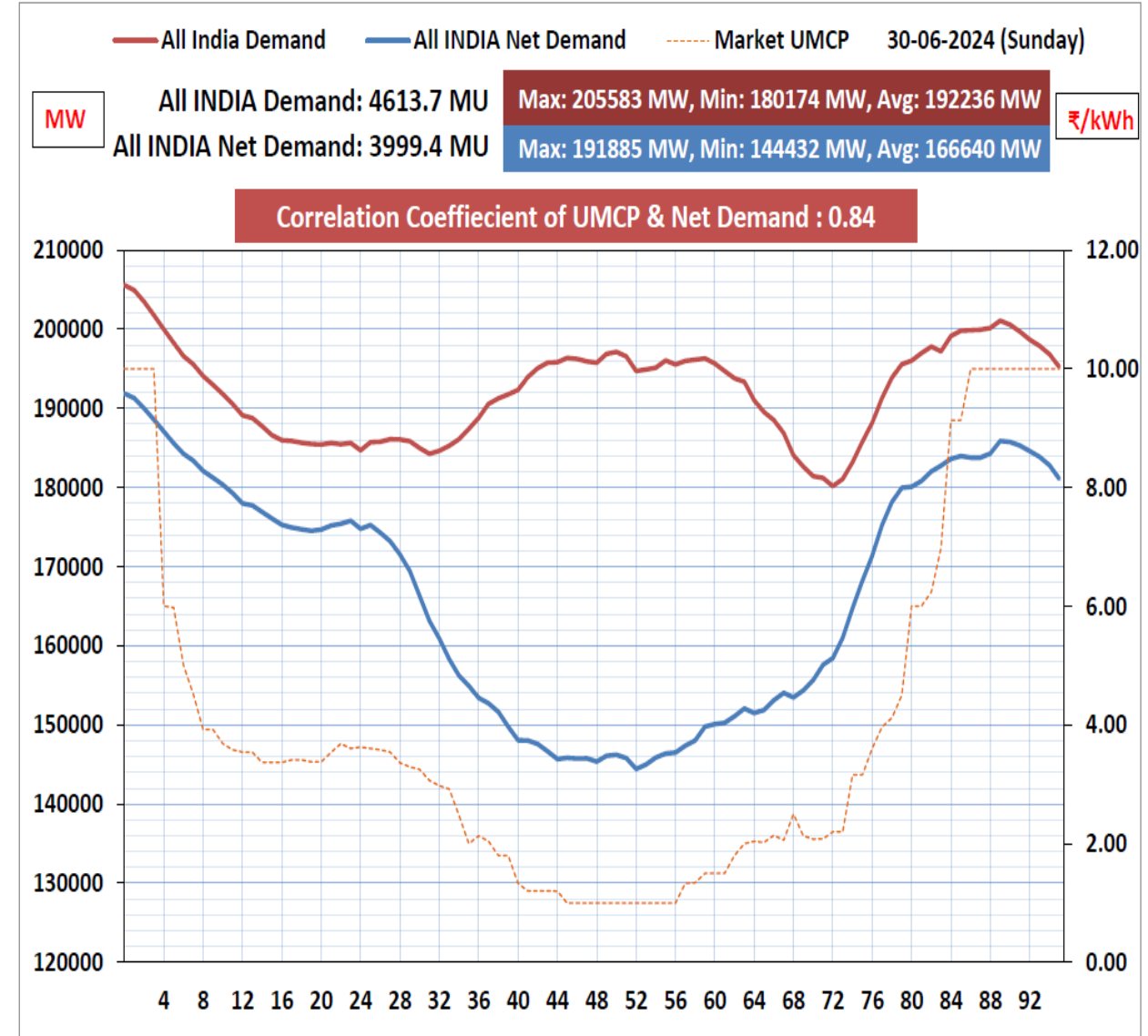
- Ensure stability and reliability of the grid through accurate VRE power & demand forecasting: Resource adequacy, Shutdown Management, RE curtailment, Switching of Lines and reactive Power Compensation devices
- Congestion Management : Regulation of Power Flow

## Unit Commitment & Reserve Market:

- Unit commitment considering VRE power generation uncertainty & demand forecasting
- Determine reserved capacity based on forecasting results
- Forecasting accuracy influences requirement assessment and bidding

## Real-Time Market:

- Buy or sell extra VRE generated power based on updated forecasts
- Crucial for maintaining power system stability



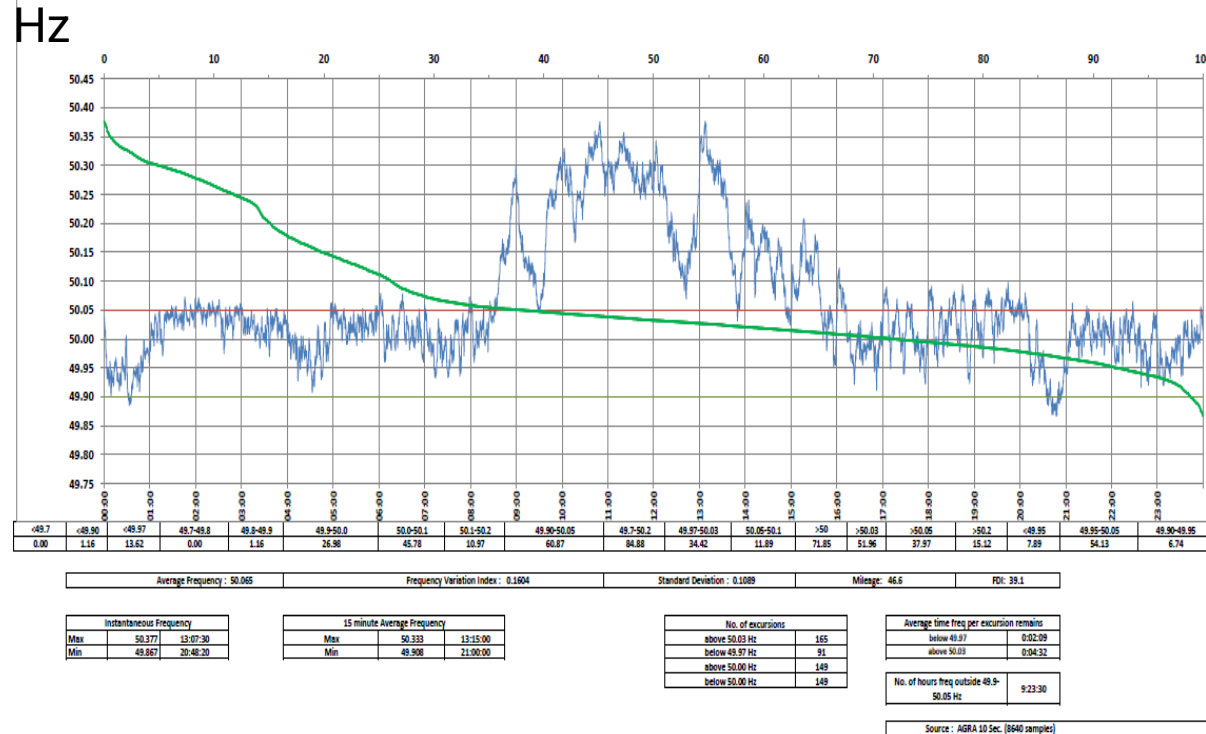
25.08.24

GRID CONTROLLER OF INDIA LIMITED

NATIONAL LOAD DESPATCH CENTRE, NEW DELHI

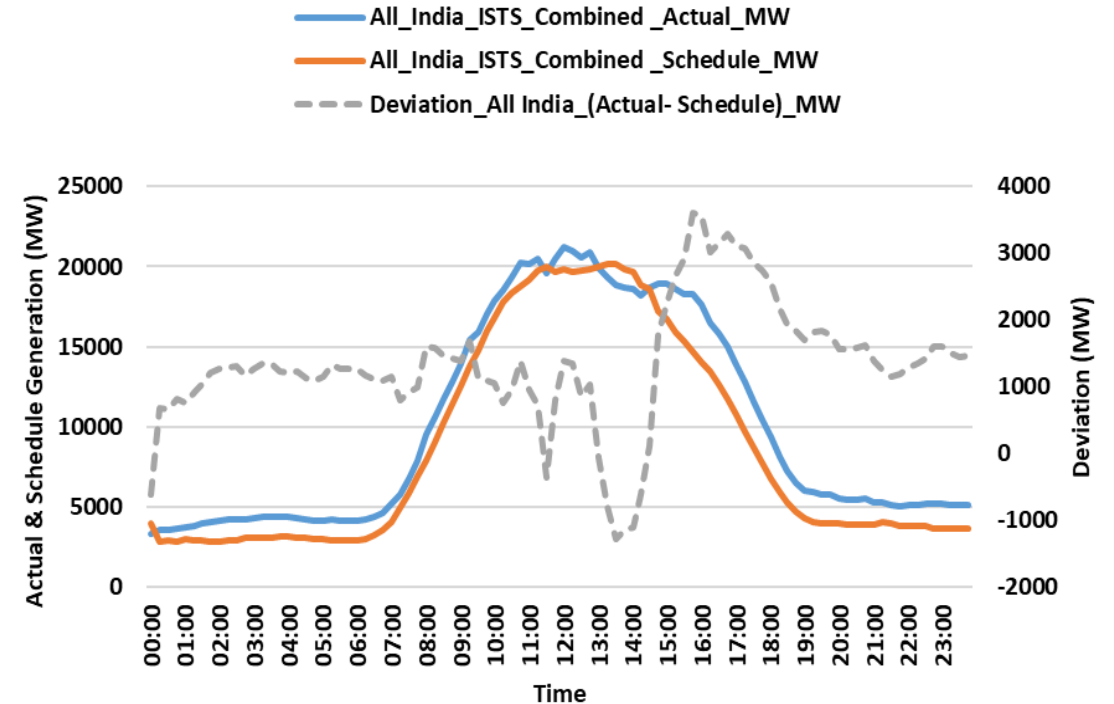


Frequency profile for 25-Aug-2024 (Sunday)



- Frequency >50.05 Hz for about **37.97% of the time during the day**
- Frequency >50.05 Hz continuously from 09:00 hrs to 14:00 hrs

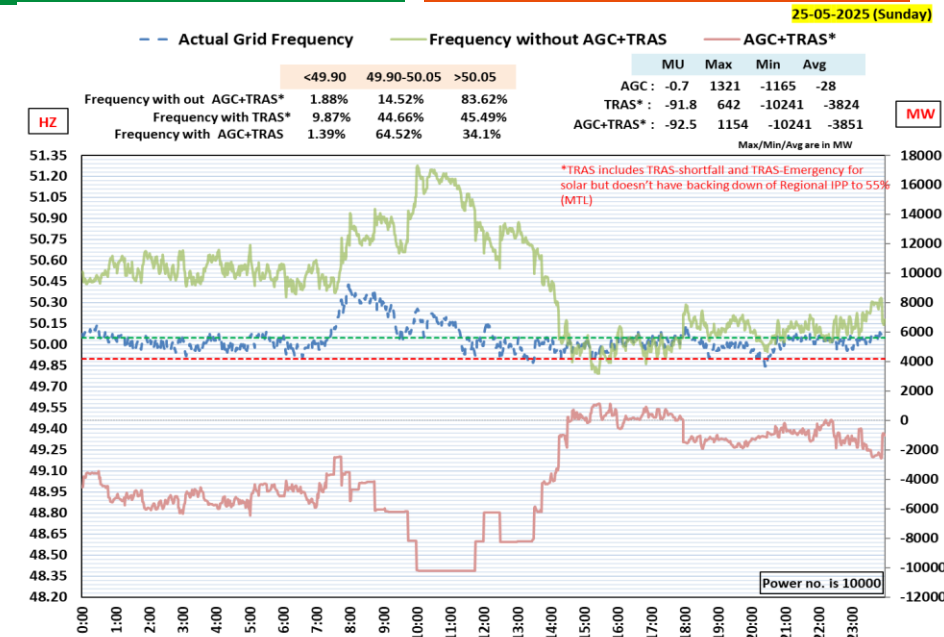
All India\_ISTS\_Combined (Solar+ Wind) Actual vs Schedule vs Deviation (on sec. axis) \_25 Aug 2024



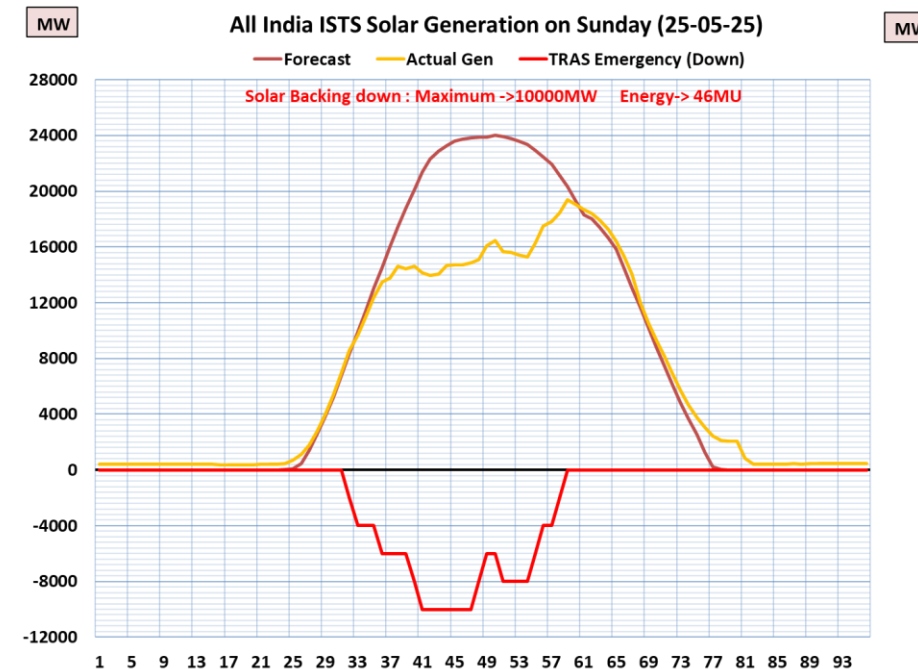
- Over injection of max **around 1500 MW** from ISTS connected RE plants during same period

# MEASURES TAKEN TO MITIGATE HIGH FREQUENCY OPERATION ON 25.05.25

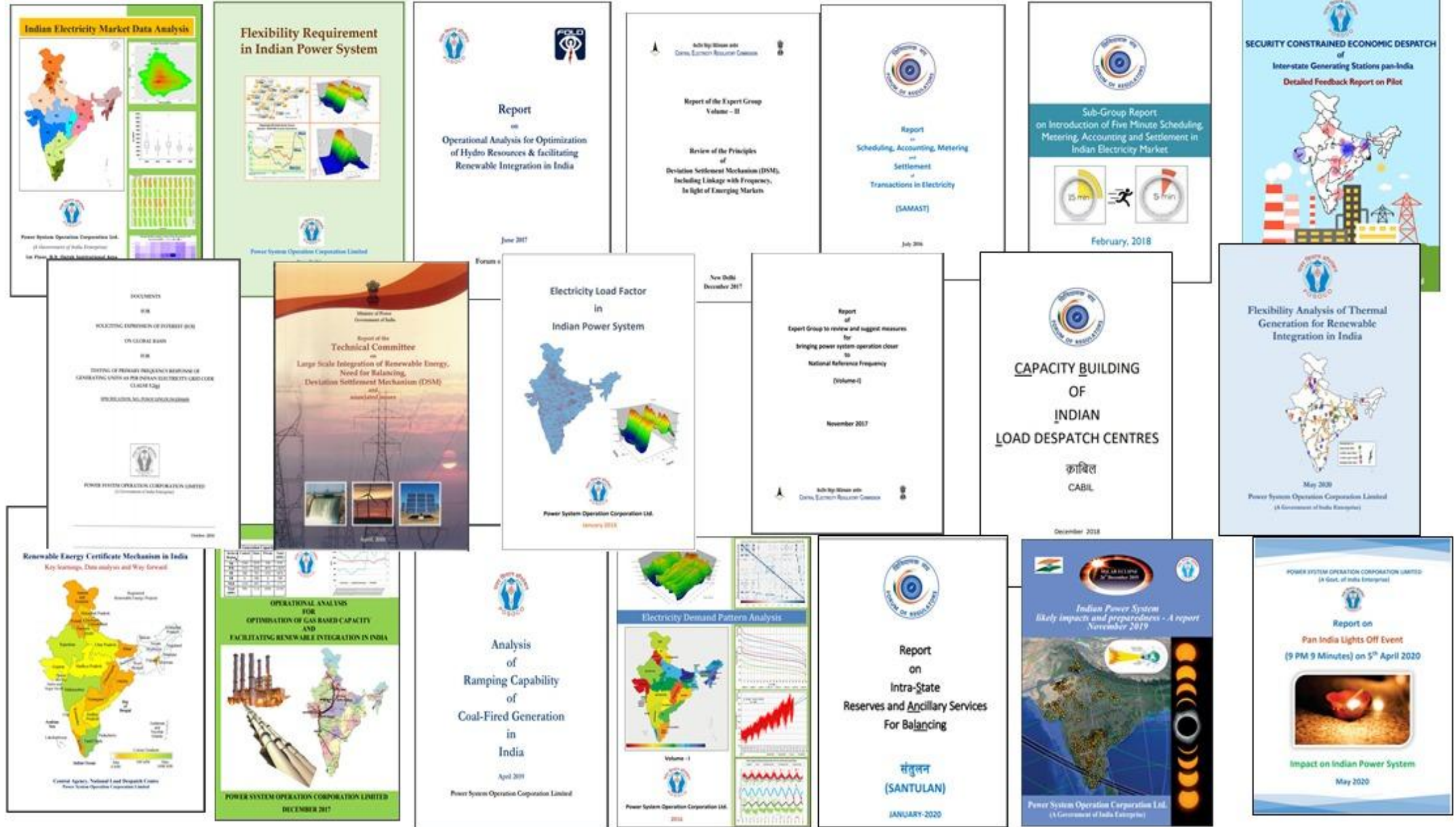
- Advisories to back down Regional IPP thermal and ISTS solar generation under TRAS (emergency) provisions.
- Advisory to states for maintaining load generation balance and flexing the thermal and hydro generators.
- Convening of a meeting with ISTS-connected solar plants to discuss real-time operational challenges and emergency RE (solar) backing down protocols.
- ISGS thermal generation reduced to 55% via TRAS (shortfall).
- Regional IPP thermal plants brought down to 55% under TRAS (emergency).
- ~10 GW of ISTS solar generation reduction under TRAS (emergency).
- Even with these measures, the grid frequency reached a maximum of 50.48 Hz
- ISTS connected 60 solar Plants capacity ~20 GW (Plant capacity 250 MW and above) given TRAS Down instruction.
- Emergency TRAS down instruction issued from 0800 hrs ~ 2 GW to 1600 hrs ~ 1GW
- Maximum Emergency TRAS down instruction ~ 10 GW from 1000hrs – 1200 hrs and in energy terms ~45 MU
- ISTS Solar curtailment w.r.t All INDIA Solar Generation(349.5 MU) is 12.87% and w.r.t All India ISTS Solar Generation(165.6 MU) is 27.17%.

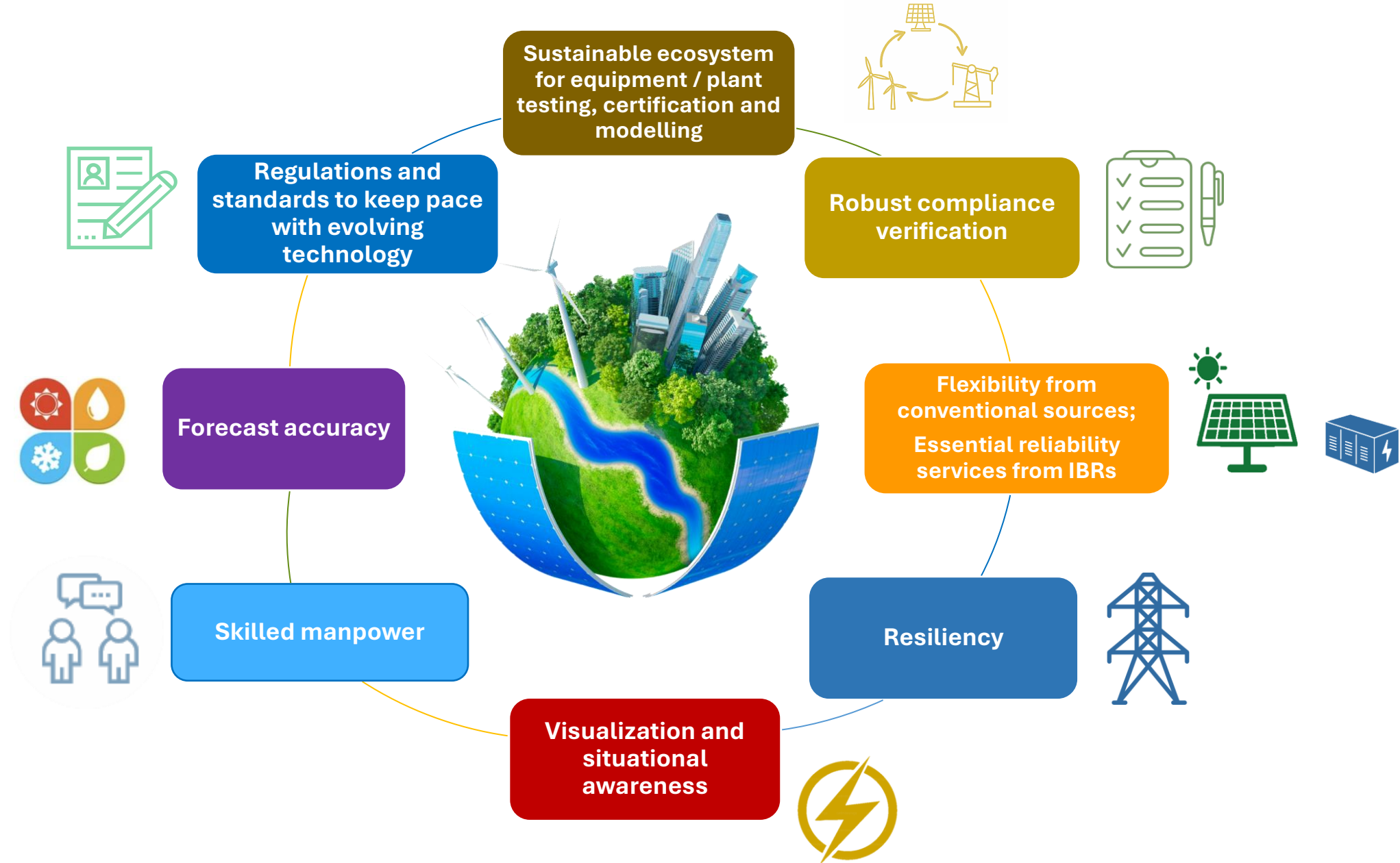


**If AGC, TRAS (SF) & TRAS (Emergency) have not been despatched then frequency would have remained 84% time above the band and ~15% within the band!!**



# OUR HUMBLE CONTRIBUTIONS TO THE COLUMN OF KNOWLEDGE





# THANK YOU!!



[www.grid-india.in](http://www.grid-india.in)

